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SUPERSONIC FLUID FLOW IN RADIAL DIFFUSERS OF CENTRIFUGAL COMPRESSORS

M. Skvor

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16. Abstract The paper discussed the theoretical solution to the problem of a supersonic flow in radial diffusers of centrifugal compressors. It also presents a summary of existing types of diffuser designs. Solutions are found for the development of the flow in a radial vaneless diffuser and the passage through a circular shock wave in the region m>1. The flow is classified on the basis of the characteristic number m (radial component of Mach number) and the critical flow angle α^*. Solutions are obtained for the shockless flow through a radial cascade, the passage of shock waves and weak disturbances through a source-vortex flow and their interaction. The supersonic part of the flow field behind the shockwave is calculated by the method of characteristics. The results obtained are illustrated graphically in velocity diagrams for the airflow.

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Notation Used:

w, u, v	-- velocity and velocity components
λ, (u/a^*), (v/a^*)	-- dimensionless velocity and dimensionless velocity components
P, ρ, T	-- state variables, pressure, density, temperature
a	-- velocity of sound
m	-- radial component of Mach number
O	-- center of flow
r	-- polar coordinates
R	-- gas constant
q	-- dimensionless flow density
α	-- flow angle in polar coordinates
β	-- shock wave angle
κ	-- adiabatic exponent
μ	-- Mach angle

Indexes

0	-- state at rest
1	-- initial state
M	-- state on boundary circle
MAX	-- maximum value
MIN	-- minimum value
*	-- critical state
'	-- state behind shock wave

SUPERSONIC FLUID FLOW IN RADIAL DIFFUSORS
OF CENTRIFUGAL COMPRESSORS

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1. Introduction /144

The contemporary trend in the development of turbocompressors is toward the continual reduction of structural sizes. This can be achieved through a reduction of the number of stages and the use of impellers with higher circumferential velocities. An increase in the compression ratio in one stage, leads, especially in fluids at subsonic velocities, to supersonic velocities during the flow through the machine.

Supersonic velocities in radial turbocompressors can be obtained by two methods:

a. vector addition of sufficiently high velocities during the transition from one kinematic system to another (during the transition from absolute motion to relative motion or vice versa, i.e. at the impeller inlet or outlet) which is independent of the shape of the impeller passage between the vanes.

b. conversion of a part of the fluid flow enthalpy to the corresponding amount of kinetic energy within the same kinetic system, for example by the proper shaping of the impeller passage between the vanes.

In the impeller the fluid acquires great kinetic energy, which is mainly converted into a pressure head in other stages of the diffuser. The task of the diffuser is to realize this conversion with maximum possible efficiency. Compression in the diffuser is complicated by the presence of a boundary layer on the walls of a comparatively very narrow duct, which becomes even thicker due to the adverse radial pressure gradient, the shock waves and their

* Numbers in the margin indicate pagination in the foreign text.

mutual interaction. It was deduced from two-dimensional isolated sections and diffusers that for Mach numbers greater than 1.25, the interaction of the shock wave and boundary layer leads to flow separation from the walls of the diffuser duct and the origin of reverse flow.

The development of radial difussers for centrifugal compressors evolved in accordance with the requirements which ensured the required compression in one stage. From the design and aerodynamic standpoint, the simplest type is a vaneless diffuser. It decelerates in the flow range $m>1$ supersonic velocities to subsonic velocities without a shock. For comparatively small compressions it has a relatively wide operating range, from choking to pumping, and an acceptable efficiency. For compressions greater than 2, the range and efficiency are limited by the instability of the radial velocity profile. Vaneless diffusers can have parallel or shaped walls (theoretically they can ensure flow without separation).

The use of flat or curved blades in the diffuser can accelerate the compression, reduce the dimensions of the machine and reduce frictional losses. At higher compression ratios the entire load can be distributed on two or more cascades connected in tandem. The operating mode of the machine can be adjusted by turning the blades (primarily in the zone of the leading edge).

Recently comparatively good results were obtained using channel and tube diffusers. Although they do not respect the vortex character of the flow, they adapt best to the nonuniform velocity profile at the impeller outlet. Further improvement was achieved by appropriate shaping of the leading edges of the blades.

Shock waves in the intake of the radial diffuser cascade can be avoided by using a sufficiently large series connected diffuser
(to induce shockless deceleration from supersonic velocities to /145

subsonic velocities) or a rotary vaned difusser in the supersonic velocity range (the relative flow velocity is subsonic).

The flow in supersonic radial diffusers is the result of the mutual interaction of the impeller, the diffuser, the return channel, additional stages and the operating mode of the stage. The greatest unsolved problem is that for inlet Mach numbers greater than 1.2, almost one half of the final increase in the static pressure occurs in the part between the leading edge and the sonic throat, i.e. only along 10% of the diffuser path.

This implies that the remaining unsolved key problem is the proper shaping of the intake of the radial supersonic cascade in view of the nonuniform velocity profile at the impeller outlet. In genreal, we are dealing with a three-dimensional nonuniform flow of a viscous compressible fluid in comparatively narrow channels in which viscosity effects are clearly evident. For the time being, a complex solution of the problem described cannot be obtained. Therefore, individual partial solutions based on appropriate simplifying assumptions must be obtained. This article assumes that the flow at the impeller outlet can be modeled approximately by a plane potential flow of an ideal compressible fluid obtained from a superposition of the source-vortex flow.

2. Potential Source-Vortex Flow in Vaneless Diffuser

Generally the flow of an ideal compressible fluid in a radial vaneless diffuser can be represented as a stationary adiabatic uniform plane flow in which particles of the fluid emanate from one point in all directions along straight or curved trajectories which can be modeled by a superposition of the potential flow of the source and vortex.

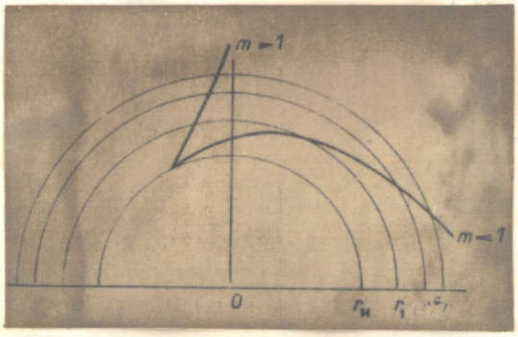

Fig. 1: The notation for parameters of source-vortex flow

The potential source-vortex flow is symmetric about the center, all /146
streamlines are identical and can be derived from one another by rotation about the center of the flow O. The notation for the parameters of the flow is given in Fig. 1. The solution shows that two basic types of flow exist which are basically different in their properties. They lie in the physical plane outside the boundary circle and one type cannot make the transition to the other. Their characteristic attribute is the radial component of the Mach number m. The boundary circle m = 1 is the limiting case of the flow. In the flow range m < 1, due to the deceleration of the flow, the particles of the fluid move along curves which are general spirals and approach asymptotically a logarithmic spiral with the angle α_o. However both subsonic and supersonic velocities occur in the flow field and the transition from supersonic velocities to subsonic velocities occurs via isentropic passage through the sonic circle. With the acceleration of the flow in the flow region m > 1, the particles move along curves which approach asymptotically radial rays. Only supersonic velocities occur in the flow field and the transition from supersonic velocities to subsonic velocities can only occur via nonisentropic passage through the circular shock wave.

To calculate the parameters of the flow at an arbitrary point of the flow field, five independent equations describing four conservation laws and one state equation are needed. The following relations can be used to describe the relations among the parameters of the flow on individual radii.

$$\varrho_1 w_1 r_1 \sin \alpha_1 = \varrho w r \sin \alpha = \varrho^* w^* r^* \sin \alpha^*, \quad (1)$$

$$w_1 r_1 \cos \alpha_1 = w r \cos \alpha = w^* r^* \cos \alpha^*. \quad (2)$$

$$\frac{\varkappa}{\varkappa-1}RT_1+\frac{w_1^2}{2}=\frac{\varkappa}{\varkappa-1}RT+\frac{w^2}{2}=\frac{\varkappa}{\varkappa-1}RT^*+\frac{w^{*2}}{2}, \quad (3)$$

$$\frac{p_1}{\varrho_1^{\varkappa}}=\frac{p}{\varrho^{\varkappa}}=\frac{p^*}{\varrho^{*\varkappa}}, \quad (4)$$

$$p_1=\varrho_1 RT_1,\quad p=\varrho RT,\quad p^*=\varrho^* RT^*. \quad (5)$$

Equations (1) and (2) can be used to obtain the characteristic flow magnitudes, i.e. the radius of the sonic circle r* and the critical flow angle α* attained by the flow during the passage through the sonic circle:

$$r^*=r_1\cdot q(\lambda_1)\cdot\frac{\sin\alpha_1}{\sin\alpha^*}, \quad (6)$$

$$\alpha^*=\mathrm{arctg}\left[\frac{\varrho_1}{\varrho^*}\,q(\lambda_1)\cdot\mathrm{tg}\,\alpha_1\right]. \quad (7)$$

Solving equations (1)-(5) and using the critical parameters of the flow in equations (6) and (7), we can write down the relations for the calculation of all unknown parameters of the flow on an arbitrary radius of the flow field in the form:

$$\left(\frac{r}{r^*}\right)^2=\frac{\sin^2\alpha^*+\cos^2\alpha^*\cdot\left[\frac{(\varkappa+1)-(\varkappa-1)\lambda^2}{2}\right]^{2/(\varkappa-1)}}{\lambda^2\cdot\left[\frac{(\varkappa+1)-(\varkappa-1)\lambda^2}{2}\right]^{2/(\varkappa-1)}}, \quad (8)$$

$$\alpha=\mathrm{arctg}\left\{\frac{\mathrm{tg}\,\alpha^*}{\left[\frac{(\varkappa+1)-(\varkappa-1)\lambda^2}{2}\right]^{1/(\varkappa-1)}}\right\}, \quad (9)$$

$$\frac{T}{T^*}=\left[\frac{(\varkappa+1)-(\varkappa-1)\lambda^2}{2}\right], \quad (10)$$

$$\frac{\varrho}{\varrho^*}=\left[\frac{(\varkappa+1)-(\varkappa-1)\lambda^2}{2}\right]^{1/(\varkappa-1)}, \quad (11)$$

$$\frac{p}{p^*}=\left[\frac{(\varkappa+1)-(\varkappa-1)\lambda^2}{2}\right]^{\varkappa/(\varkappa-1)}. \quad (12)$$

The behavior of the source-vortex flow can be illustrated graphically in the dimensionless velocity diagram presented in Fig. 2. /147
The boundary curve separating the flow regions m < 1 and m > 1 is an ellipse with semiaxes $\lambda = 1$ and $\lambda = \lambda_{Max}$.

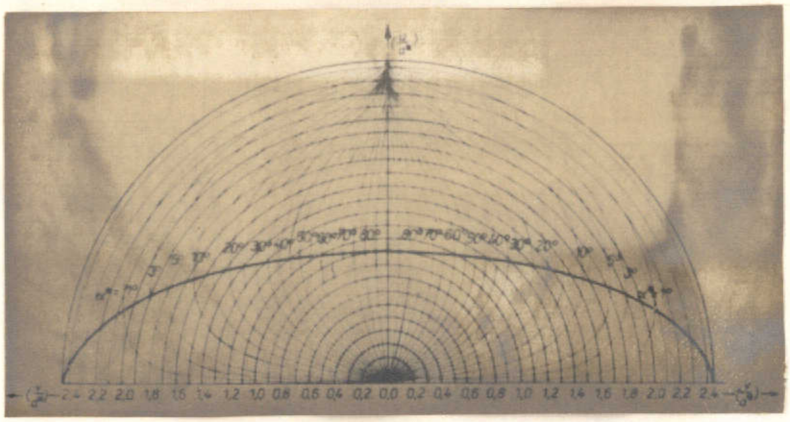

Fig. 2: The source-vortex flow in the hodograph diagram

In a uniform source-vortex flow, because of central symmetry, only a circular shock wave with center at the flow center O can arise in a vaneless difusser. Its properties are analogous to those of an oblique shock wave in a uniform parallel flow. Since during the passage through an oblique shock wave the perpendicular velocity component must be supersonic, the circular shock waves can only arise in the region m > 1. In spite of the fact that we are dealing with a curved shock wave, the flow behind the shock wave is not turbulent and it can again be characterized as a potential source-vortex flow. During the passage through the circular shock wave, the flow with critical flow angle α^* in the flow region m > 1 in which the flow accelerates makes the transition to a flow with critical angle $\alpha_2{}^*$ in the flow region m < 1 in which the flow decelerates. The position of the circular shock wave in the flow field depends on the magnitude of the counterpressure. The passage through the circular shock wave can again be illustrated graphically in a dimensionless velocity diagram given in Fig. 3. /148

3. Shockless Flow Through Radial Cascade

During the shockless flow through a static circular cascade consisting of an infinite number of infinitesimally thin vanes,

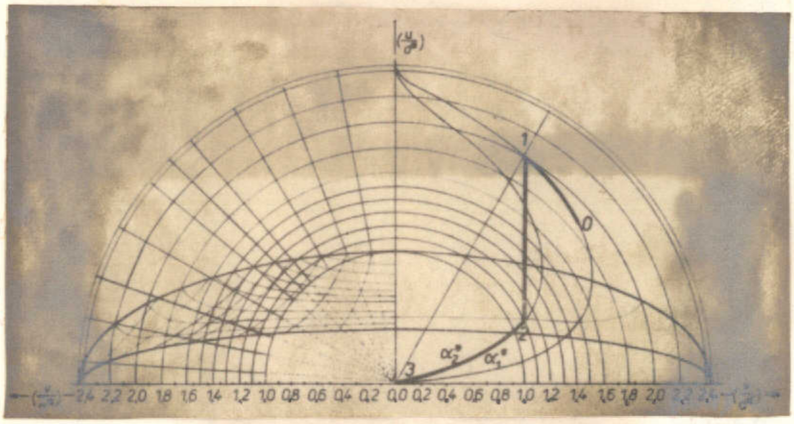

Fig. 3: Passage of source-vortex flow through circular cascade

0. initial supersonic expansion state
1. state in front of shock wave
2. state behind shock wave
3. final subsonic compression state

the potential compressible source-vortex fluid flow with critical flow parameters r_1^*, α_1^* makes the transition to another potential flow with critical parameters r_2^*, α_2^*. The cascade inlet angle α_1 corresponds to the flow angle on the cascade inlet radius r_1 and the cascade outlet angle α_2 gives the flow angle on the outlet radius r_2 (Fig. 4). Because of the special geometry of the circular cascade, the flow parameters change during the flow through the circular cascade due to the flow around individual profiles and the natural change of the radius. In the graphical representation these effects can be separated from one another. The change in the flow parameters due to the effect of the radius will be determined in accordance with Fig. 2 and the change in the parameters due to the circular cascade itself in accordance with Fig. 5. The flow through the circular cascade will be obtained from a superposition of both partial solutions. The graphical representation is given in Fig. 6.

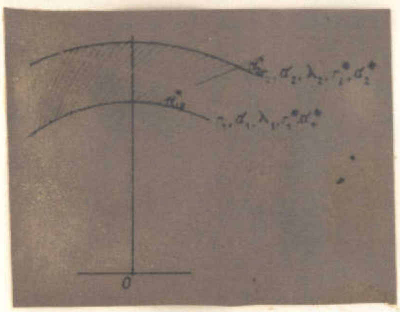

Fig. 4: The notation for parameters of circular cascade

4. Supersonic Flow in the Intake of a Radial Diffuser Cascade

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The flow in the intake of a radial cascade with a finite number of vanes of finite thickness with a sharp leading edge represents a

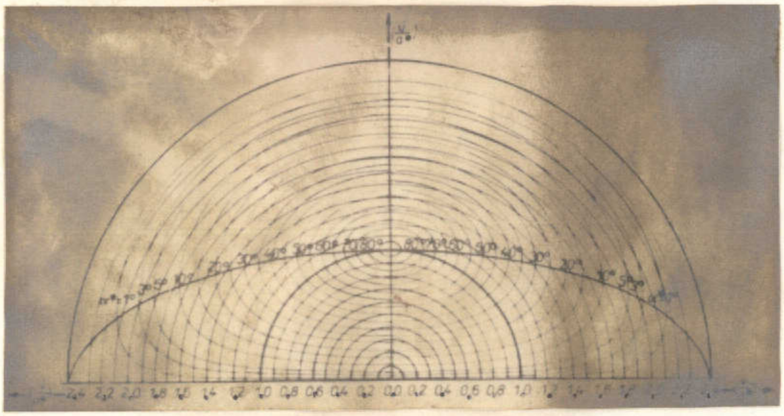

Fig. 5: The effect of a circular cascade on change in parameters of the flow

flow around a finite number of profiles spaced evenly along the cascade inlet circle. When the supersonic source-vortex flow is incident to the circular cascade, a system of shock waves develops on the leading edges of the vanes, which propagates from the leading edges to the flow field.

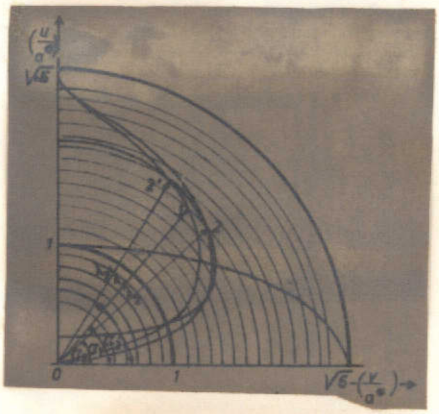

Fig. 6: Representation of the flow through the circular cascade in the hodograph diagram.

1. state of flow on cascade inlet radius r_1
$\widehat{12'}$ change in flow parameters due to the effect of radius
$\widehat{2'}2$. change in flow parameters due to the effect of cascade
2 state of flow on cascade outlet radius r_2

These shock waves interact with the inhomogeneous inflow and the disturbances from the profiles. As a result of this interaction the shock wave becomes curved and a very complex flow field is formed which is always turbulent behind the shock wave. The decisive quantity determining the configuration of the shock waves is the characteristic number m of the source-vortex flow. To prevent perturbation of the inflow, no disturbance from the profile must point in the direction of the region in front of the cascade.

The interaction of the shock wave and the source-vortex flow can be illustrated schematically as in Fig. 7. A connected series of primary reflected disturbances and tangential discontinuities is formed during this interaction. The primary reflected disturbances which, depending on the character of the incident flow, can be compression or expansion waves, propagate through the inhomogeneous flow region behind the shock wave and interact with the tangential discontinuities. During the interaction the primary disturbances become curved and additional secondary reflected disturbances are formed. After the primary reflected disturbance impinges on the profile, the reflection or absorption of the disturbance obeys the same laws as in a two-dimensional parallel flow.

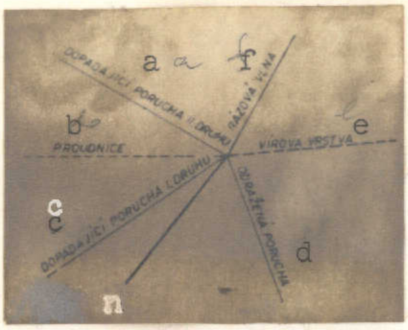

Fig. 7: The pattern of the interaction of a shock wave with the potential source-vortex flow

Key: a. incident disturbance, type II
b. streamline
c. incident disturbance, Type I
d. reflected disturbance
e. vortex layer
f. shock wave

When no disturbance from the profile passes through the flow field behind the shock wave, the shape of the shock wave is completely determined by the source-vortex flow parameters at the point of incidence on the vane and the initial intensity of the wave. The integral curves giving the change in the shock angle β as a function of the dimensionless velocity λ of the incident flow are plotted for a flow with $\alpha^* = 20^0$ in Fig. 8. The straight line $\lambda = \lambda_{Max}$ separates the field into the flow regions m < 1 and m > 2. The interaction model presented can only be used at points where a supersonic velocity $\lambda' > 1$ arises behind the shock wave, since the reflected disturbances can only pass through a supersonic field. Since no reflected disturbances pass from the curve $\lambda' = 1$ through the region behind the shock wave, we can assume with a certain degree of approximation that during the passage through the shock wave the solution continues along the curve on which the change in the pressure is constant. In particular this assumption will be satisfied by relatively weak shock waves, where we can again assume a /151

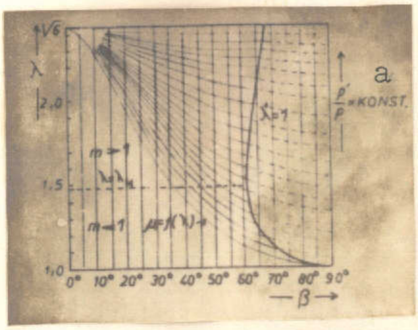

Fig. 8: The passage of a shock wave through the potential source-vortex flow

a. const.

potential source-vortex flow behind the shock wave (of course with a different entropy value). Hence a certain minimum value λ_{Min} of the dimensionless velocity corresponds to every initial state of the shock wave $[\lambda, \beta]$ at the point of incidence on the vane.

Up to this point the interaction of the shock wave with the inhomogeneous flow can be solved using the method presented. For the time being it is not possible to make an exact statement about the propagation of the shock wave from the point $\lambda' = 1$ to the sonic circle. It can either propagate as a perpendicular shock wave with respect to the velocity vector at the given point, or the incident flow may be modified.

At some flow field points the integral curves and the curves of constant shock intensity have a common tangent. These are points at which the shock intensity is a maximum or minimum. At these points the character of the shock wave intensity changes and no disturbances are reflected to the flow field behind the shock wave. An example of the characteristics and shock waves of different intensity for the case of a flow with $\alpha^* = 20^\circ$ in the region $m < 1$ is given in Fig. 9 and the flow in the region $m > 1$ in Fig. 10. /152

An example of an approximate calculation of the supersonic part of the flow field behind the shock wave in the region $m < 1$ using the method of characteristics in the zone where the flow impinges on the radial cascade is given in Fig. 11. To prevent disturbances of the inflow, the side of the vane facing the impinging flow must be designed in the shape of the entering streamline.

When also weak disturbances from the profile pass through the

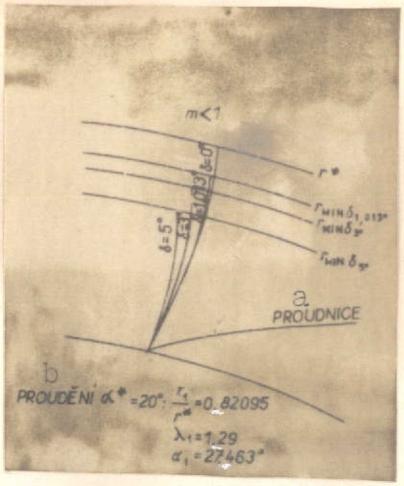

Fig. 9: Shock waves and characteristics in the region m < 1

Key: a. streamline
b. flow

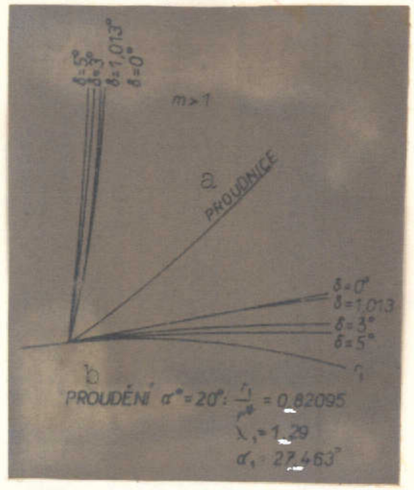

Fig. 10: Shock waves and characteristics in the region m > 1

Key: a. streamline
b. flow

flow field behind the shock wave, an additional interaction between the shock wave and the weak wave occurs at the point where it impinges on the shock wave. Additional reflected disturbances and tangential discontinuities arise during this interaction. After this interaction the solution for the passage of the oblique shock wave through the potential source-vortex flow in Fig. 8 follows a different integral curve.

Conclusion /153

During the last decade considerable progress was made in improving the performance of radial turbocompressors. In the beginning the development trend was primarily determined by the requirements for the design of aircraft engines, however today it is shifting toward turbocompressors for various industries. The current objective is to improve the adiabatic efficiency at the

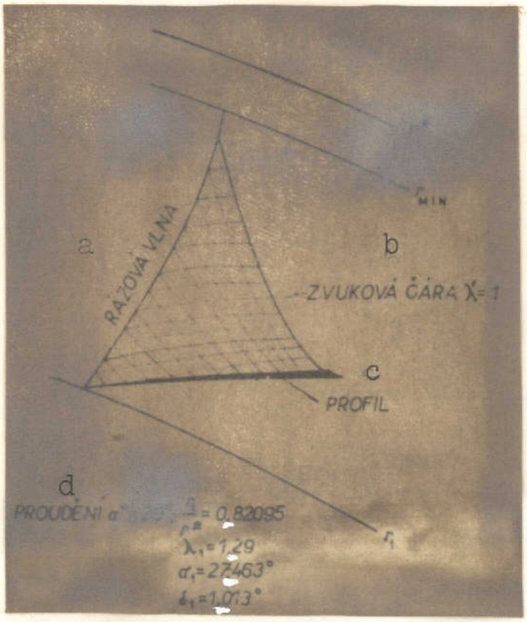

Fig. 11: The approximate calculation of the flow field behind a weak shock wave by the method of characteristics in the region m < 1

Key: a. shock wave
b. sonic line
c. profile
d. flow

calculated point by about 80% in compressors with an 8:1 compression ratio and by about 75% in compressors with a 10:1 compression ratio. Insufficient knowledge about the flow through individual parts of centrifugal compressors prevents us from developing for the time being an efficient computational method ensuring good aerodynamic characteristics of the compressors, especially at transonic and supersonic velocities. For this reason extensive systematic theoretical and experimental research is needed, whose objective is to furnish the required basis for the design of modern equipment operating with high efficiency in a sufficiently wide neithborhood of the design point.

A complex solution of the problem presented cannot be obtained at the present time. Therefore the individual partial solutions must be obtained on the basis of certain simplifying assumptions and the research must be carried out using properly designed experimental equipment. The results of the research must be verified by measurements made on model stages or if necessary on ready equipment.

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